

Distribution and characteristics of loess landslides triggered by the 1920 Haiyuan Earthquake, Northwest of China

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ABSTRACT

On December 16, 1920, an earthquake with a magnitude of 8.5 occurred in Haiyuan County, Ningxia Hui Autonomous Region, Northwest of China. This earthquake triggered several thousand loess landslides which resulted in thousands of deaths and blockages of rivers. The distribution and characteristics of the landslides triggered by the Haiyuan Earthquake in loess areas were studied using satellite images and field investigation. A total of about 3,700 landslides with a cumulative area of about 177 km² were interpreted over an area of 21000 km². It was found that landslides triggered by the earthquake were concentrated in a western of 40-55 km from the

Haiyuan fault. Landslides were concentrated near ridge crests, with 65.7% of the landslides originating in the upper quadrant of slopes. The aspects of the landslides triggered by the Haiyuan Earthquake were parallel to the faults and there is no back-direction effect in landslides triggered by Haiyuan earthquake. These landslides have long run-out distances (travel distance (L) / height different (H) > 0.6) and deposited materials in river channels, forming 51 dammed lakes that still exist. The relationship between the area (A) and volume (V) of the landslides is $V=4.170\times A^{1.086}$. Based on the relationship between number and volume of landslide and the magnitude of earthquake, more than 100,000 landslides with a cumulative volume of $0.5\times 10^{10}\text{m}^3$ were triggered by the Haiyuan Earthquake. As loess is sensitive to liquefaction during an earthquake and tends to produce landslides with long travel distances. Hence, the loess depth, slope and geological stresses are the primary factors responsible for the high density of landslides in this region.

Keywords

Coseismic loess landslide; Distribution; Characteristics; Haiyuan Earthquake

1. Introduction

Loess is distributed in arid and semi-arid regions and formed by the accumulation of wind-blown fine sand and clay components. The Loess Plateau has an area of approximately 430,000 km² and constitutes the main part of the loess area in China (Liu, 1985). The thickness of loess deposits in this area varies from few meters to more than 300 m (Derbyshire, 2000; Li et al., 2013). Loess is characterized by macro-pores, vertical joints, loose texture and silt content of more than 50%, which makes it sensitive to earthquakes and consequent landslides (Zhang and Wang, 1995; Derbyshire, 2000; Dijkstra 1995; Xu et al., 2007; Zhang and Wang, 2007; Zhang et al., 2009; Zhuang et al., 2016). The Loess Plateau in China is located in the Orodos Block, which

is bounded by an active earthquake zone and many earthquakes with magnitudes of higher than 6.0 have been reported in this area, and most of the loess landslides in this area are known to have been triggered by historical earthquakes (Derbyshire, 1991; Li et al., 2009; Liu et al., 2015; Li et al., 2015). Some examples of strong earthquakes in this region include the Hongdong County Earthquake in 1303 ($M_w=8.0$), Hua County Earthquake in 1556 ($M_w=8.0$), Tianshui City Earthquake in 1654 ($M_w=8.0$), Tongwei County Earthquake in 1718 ($M_w=7.5$), Haiyuan County Earthquake in 1920 ($M_w=8.5$), and Gulang County Earthquake in 1927 ($M_w=8.0$, Xie and Cai, 1983; 1985; 1987a, 1988b). Each of these earthquakes triggered more than 10,000 loess landslides with more than 40,000 casualties (Liu et al., 2003).

On December 16, 1920, a strong earthquake of $M_w 8.5$ (Zhang et al., 1987) occurred in Haiyuan County, Ningxia Hui Autonomous Region, Northwest of China. This earthquake has been the focus of many studies (Zhang et al., 1987; Zhang et al., 1988a, 1988b; Zhang and Wang, 1995; Zhang and Wang, 2007; Zhang et al., 2009; Li et al., 2009; Liu et al., 2015; Li et al., 2015). The strongest quaking activity lasted for nearly 6 minutes (Zhang et al., 1987), with a seismic intensity of up to twelve degrees on the Chinese Seismic Intensity Scale in the meizoseismal area. About 500,000 houses and cave dwellings collapsed and a large number of houses were damaged to various extents (Seismological Institute of Lanzhou, SSB. and Seismological Team of Ningxia Hui Autonomous Region, 1980; Zhang et al., 1987). Altogether, 234,117 people died and many were injured (Seismological Institute of Lanzhou, SSB. and Seismological Team of Ningxia Hui Autonomous Region, 1980; Zhang and Wang, 1995). Many of the earthquake-hit areas are covered by loess which is more sensitive to shake (Derbyshire 2000; Zhang and Wang 2007; Zhuang et al. 2017), which resulted in occurrence of thousands of landslides in the area. These landslides

67 blocked rivers, and buried farmland and villages (Seismological Institute of Lanzhou, SSB. and
68 Seismological Team of Ningxia Hui Autonomous Region, 1980). An area of $\sim 10,700 \text{ km}^2$
69 experienced a shaking intensity of \geq ten and $\sim 21,000 \text{ km}^2$ experienced an intensity of \geq nine
70 (Seismological Institute of Lanzhou, SSB. and Seismological Team of Ningxia Hui Autonomous
71 Region, 1980).

72 Numerous studies have been done on landslides triggered by earthquakes; some of these
73 studies established correlations between the environmental parameters of the slopes and landslides,
74 influences of landform, earthquake magnitude, earthquake local geology, slope profiles, and
75 vegetation cover, e.g., Wenchuan Earthquake occurrence in 2008 (Yin et al., 2009), Yushu
76 Earthquake occurrence in 2010 (Xu et al., 2013), Chi-Chi Earthquake occurrence in 1999 (Liao and
77 Li, 2000; Lin and Tung, 2004), Northridge Earthquake occurrence in 1994 (Harp and Jibson,
78 1996), Kashmir Earthquake occurrence in 2005 (Owen et al., 2008). Other studies focused on the
79 mechanism for slope failures triggered by earthquakes using dynamic triaxial test or shaking table
80 test and simulated earthquake experiments (Wartman et al., 2005; Lin and Wang, 2006; Wang and
81 Lin, 2011). Meanwhile, other studies focused on the assessment of landslides triggered by
82 earthquakes and several models have been proposed in different areas, such as the Newmark
83 model (Jibson, 1993; Jibson and Harp, 2000). However, the characteristics and distributions of the
84 loess landslides triggered by the Haiyuan Earthquake have not been studied in depth. This is
85 because of a scarcity in data available from that period. Zhang and Wang (1995) conducted field
86 investigations in the earthquake affected areas and provided a general description of landslides
87 and barrier lakes. Some other studies focused on the mechanism behind loess landslides or used
88 individual watersheds to conduct case studies of landslide distribution (Zhang and Wang, 2007;

Wang et al., 2014). Nevertheless, the in-depth study about distribution of the loess landslide in meizoseismal area triggered by the Haiyuan earthquake in 1920, their characteristics and comparison with other earthquake-triggered landslides have not been done so far.

In this paper, we analyzed the distribution and characteristics of the landslides triggered by the Haiyuan Earthquake in 1920 based on image interpretation and field investigations. The spatial distribution of the landslides triggered by the earthquake was obtained by correlating with the influencing factors that control earthquake-triggered landslide occurrence eg, slope, aspect and distance to the fault, and the mechanisms behind their distribution and long run-out distances are discussed.

2. Study area

The area affected by the Haiyuan Earthquake is located along the northeastern margin of the Tibetan Plateau in the Ningxia-Hui Autonomous Region, Northwest of China (Figure 1). The earthquake occurred along the Haiyuan fault, which is an active left-lateral fault near the northeastern edge of the Tibetan Plateau (Burchfiel et al., 1991). The Haiyuan fault can be divided into eastern and western sections (Burchfiel et al., 1991). The western section branches of the Altyn Tagh fault in the Qilian Shan mountain range and continues eastward with a strike of around 110°. It then veers to a 140° strike east of the Yellow River and at the border of Haiyuan County (Burchfiel et al., 1991). The fault separates mountainous topography to the south with relief of up to 2900 m from low-relief areas to the north. The eastern fault zone exhibits an approximately ~155° strike and connecting it with the Liupanshan fault at the Liupanshan Mountains. Here, the fault separates bedrock and loess of the Liupanshan from loess tablelands and Quaternary sediments of the Guyuan Basin.

The M_w 8.5 Haiyuan Earthquake occurred at 20:06 on December 16, 1920 (Seismological Institute of Lanzhou, SSB. and Seismological Team of Ningxia Hui Autonomous Region, 1980; Zhang and Wang,1995). The epicenter of the earthquake was at Salt Lake (36.65° N, 105.29° E), 30 km west of Haiyuan County Town (Figure 1), with a focal depth of 26 km (Seismological Institute of Lanzhou, SSB and Seismological Team of Ningxia Hui Autonomous Region, 1980; Zhang and Wang, 1995). The strongest shaking lasted for around 6 min and produced a surface rupture extending along the Haiyuan fault from Salt Lake to Guyuan County (Zhang and Wang,1995), with a total distance of ~220 km. Coseismic surface rupture reached a maximum of about 10 m (Zhang et al., 1987).

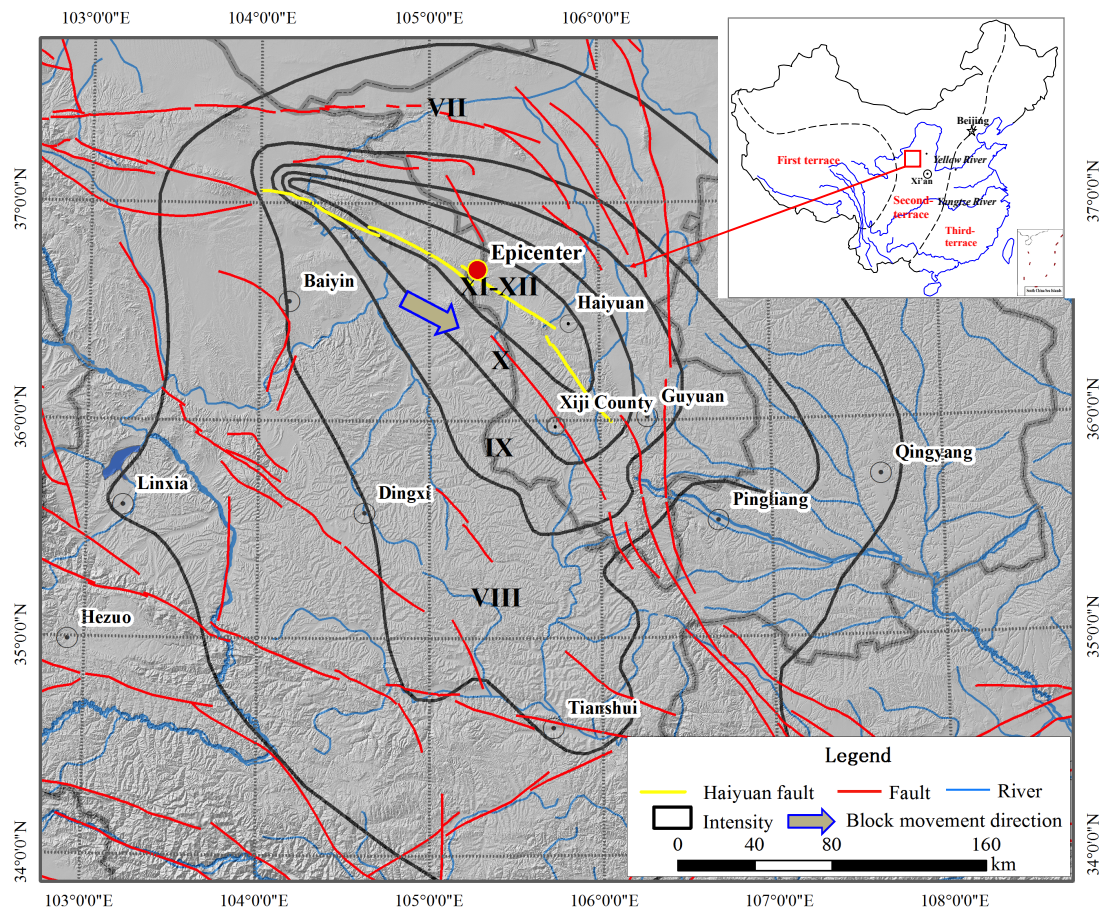


Figure 1 The landform and epicenter of the 1920 Haiyuan Earthquake

Until 1923, there were six aftershocks with a magnitude of higher than 5; the strongest had a

M_w of 7 and occurred on 25 Dec. 1920 (Seismological Institute of Lanzhou, SSB and Seismological Team of Ningxia Hui Autonomous Region, 1980; Burchfiel et al., 1991).

3. Landslide data and method

3.1 Landslide data

The earthquake produced intense shaking in a loess-covered area with high topographic relief which resulted in many earthquake-induced geohazards. The strong main quake and aftershocks as well as the large surface displacement triggered numerous landslides (Seismological Institute of Lanzhou, SSB. and Seismological Team of Ningxia Hui Autonomous Region, 1980), particularly in loess areas. In these areas, the landslides were characterized by a long travel distance (Zhang and Wang, 2007; Wang et al., 2014). Although the Haiyuan Earthquake occurred nearly 100 years prior to this study, and the loess areas within the study area have undergone rapid erosion (Zhang et al., 1991; Shi and Shao, 2000), there is still observable evidence of large landslides which were observed during field investigations. In the loess-covered area, where quake intensities were more than seven degrees, the features of landslide scars and landforms can still be identified using satellite images (SPOT, with 5m resolution and obtained 2010-2015, Figure 2) and a Digital Elevation Model (DEM, with 25 m resolution obtained 1990s). The evidence support that these landslides were triggered by the Haiyuan Earthquake are follows:

Firstly, the local people from their father or grandfather information pointed that the landslides were triggered by the Haiyuan Earthquake in 1920. Secondly, the landslides belong to loess landslide and the area is covered by a great depth of loess which is very sensitive to water and the quick landform-change during rainy seasons, if the landslide were formed more than 300

years, they would have been changed and the features of the landslide would not be obvious (eg: the loess landslides triggered by the Tianshui City Earthquake in 1654 with magnitude M_w 8.0). Thirdly, there is no large earthquake ($M_w > 7$) reported in the intensity of eight of the Haiyuan Earthquake hit-areas in 1920 nearly 700 years before 1920 (Zhang et al., 1987; Burchfiel et al., 1991). So, we take the intensity of 8 of the Haiyuan Earthquake in 1920 as example to study the loess landslide triggered by earthquake, their distribution and characteristics. There are some large earthquake events outside intensity of 8 of the Haiyuan M_w in 1920, eg the Gulang Earthquake with the M_w of 8.0 in 1927, the Tongwei Earthquake with the M_w of 7.5 in 1718, the Tianshui Earthquake with the M_w of 8.0 in 1654 (Figure 3).



Figure 2 The typical landslides triggered by 1920 Haiyuan Earthquake and the features are still visible

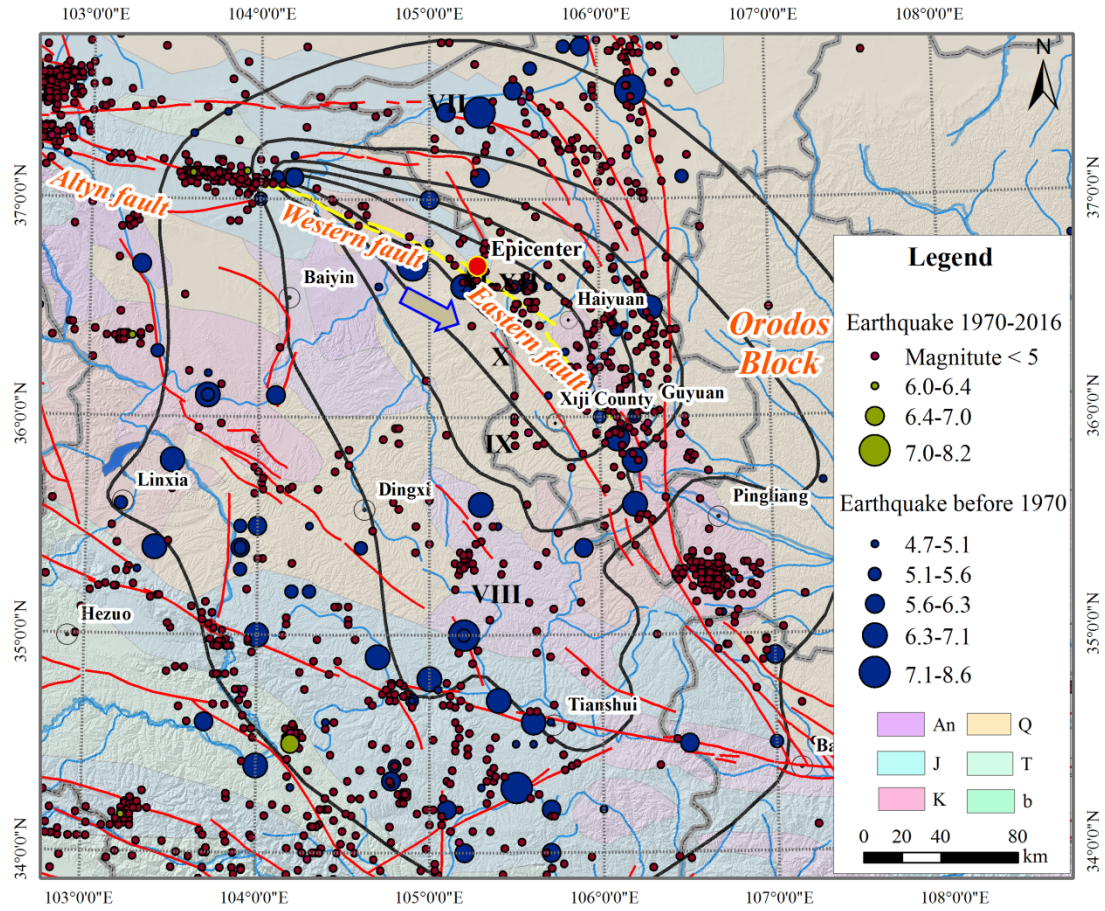


Figure 3 The history of earthquakes and faults around the 1920 Haiyuan Earthquake

3.2 Method

Landslide data were obtained from image interpretation followed by field investigations. The landslides were interpreted from satellite images using the technique of the rear wall of landslide with the notable armchair-shaped features and texture of the dislocated or discontinued contour line. Landslide data include area, location, travel distance, and height difference which were obtained by a Portable Laser Range Measuring Instrument (PLRM) during site surveys.

Landslides were measured, from the nearest ridge (d_{top}) and the nearest stream (d_{st}) from DEMs using hydrology and near tools using ArcGIS. The measured distances were normalized by the total length of the slope (Meunier et al., 2008):

$$|d_{st,top}| = \frac{d_{st,top}}{d_{st} + d_{top}} \quad (1)$$

Where, the value of d_{st} varies from 0 for a cell located in the stream network to 1 for a ridge cell. The reverse is true for d_{top} .

Landslides located along the x-axis originated near or at a ridge crest, while landslides along the y-axis connected with a river channel. Landslides near the origin of the plot indicate that they moved from the ridge to the river channel, while landslides far from both axes were in a mid-slope position (Meunier et al, 2008).

We conducted soil tests on three loess soil samples from Xiji County following the standard for Soil Test Method. Following the standards of China Method of Soil Test, the basic properties of the loess were measured. The cohesion and angle of internal friction were tested using the direct shear test method following soil test standard GBT50123-1999. The unit weight and porosity of the soil were measured using the Ring Sampler Method and bottle method.

4. Spatial distribution of coseismic landslides

4.1. Correlation between landslides and active faults

A total of 3,700 landslides were identified in this area (Figure 4). The landslides are distributed along the Haiyuan fault and mainly are concentrated along west of the fault, especially in the Xiji County.

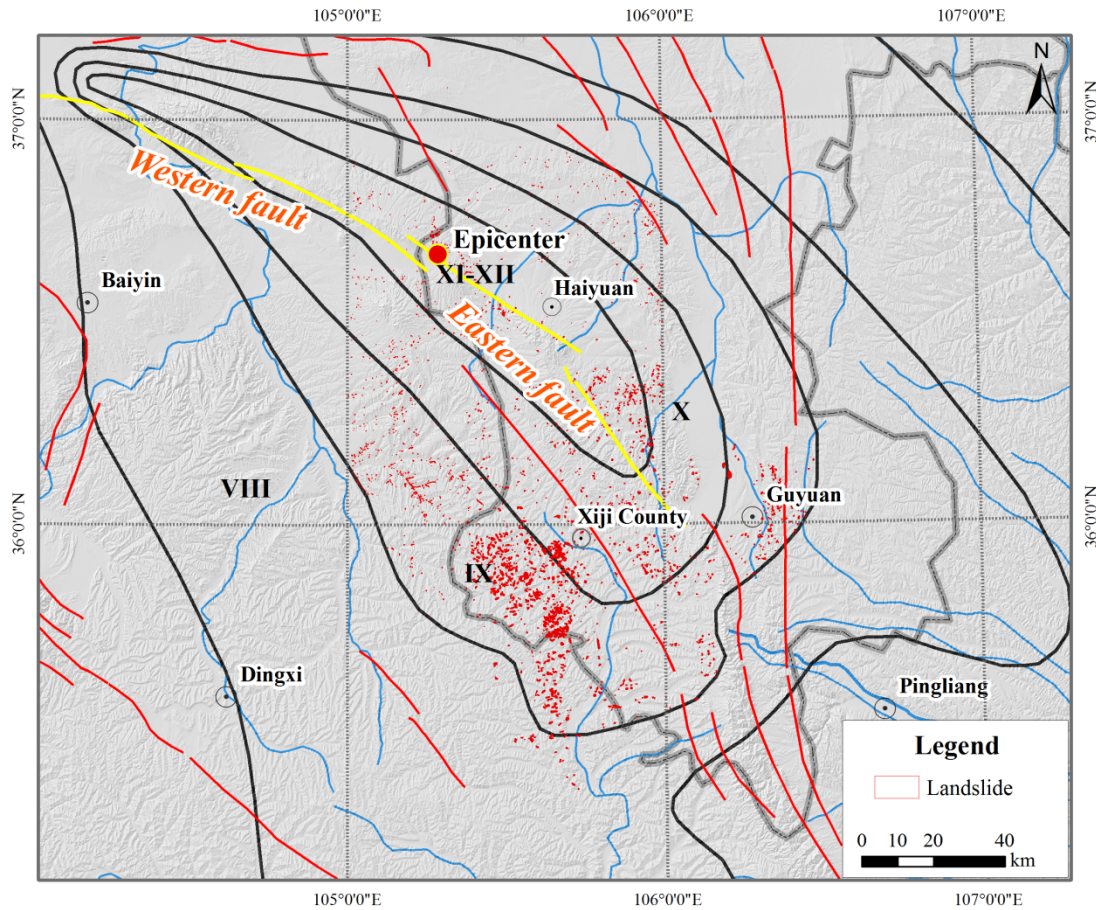


Figure 4 Landslides identified as having been induced by the Haiyuan Earthquake in 1920

It is widely recognized that the active faults play an important role in determining landslide distribution during earthquakes. This is because the quake intensity and PGA (Peak Ground Acceleration) vary at different distances from the fault. Many studies have revealed that the landslides triggered by earthquakes tend to be clustered along the corresponding fault (Harp and Jibson, 1996; Keefer, 2000, 2002; Lin and Tung, 2004; Owen et al., 2008; Zhuang et al., 2010; Qi et al., 2010; Dai et al., 2011; Gorum et al., 2011; Cui et al., 2011), and become less numerous with increasing distance from the fault (Dai et al., 2011; Chen et al., 2017). Figure 5 indicates the frequency histogram of landslides occurring within every 5 km from the Haiyuan fault. The landslides were distributed primarily along the active faults of the main Haiyuan fault, but unlike in other earthquake events, there was no clear negative correlation between landslide number and

distance from the fault. Landslides were most prevalent in a zone that was 40-55 km from the Haiyuan fault.

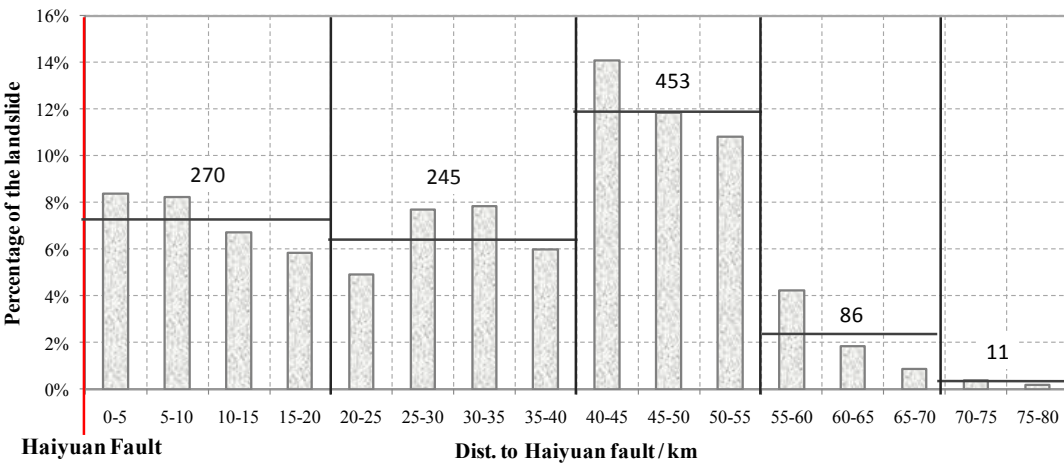


Figure 5 The landslide distribution at different distances from the Haiyuan fault

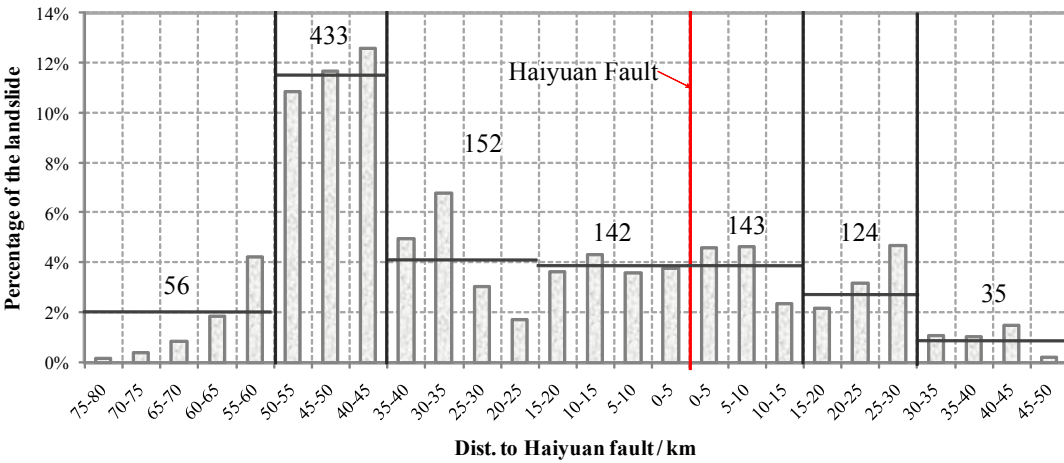


Figure 6 Landslides distribution on both sides of the Haiyuan fault

Figure 6 shows the frequency histogram of landslides occurring within every 5 km from the Haiyuan fault differentiation between the western and eastern sides of the fault. The two sides of the main fault displayed dissimilar distributions. On the western of the fault, most landslides (433 per 5 km, on average) occurred in a zone 40-55 km from the fault. Beyond 55 km, the average was only 56 per 5 km. On the other hand, on the right side of the fault exhibited a more predictable pattern with fewer landslides being recorded with increasing distance from the fault. The average

number of landslides per 5 km in the zones of 0-15km, 15-30 km and 30-50 km distant from the fault were 143, 124 and 35, respectively.

4.2. Landslide position on the slopes

Some researchers have pointed out that the landform can affect the PGA and amplified in ridges (Griffiths and Bollinger, 1979; Bouchon and Barker, 1996; Lee et al., 2008). As depicted in Figure 7, landslides were plotted to reveal the highest and lowest points of individual landslides in a frame of abscissa $|d_{top}|$ and ordinate $|d_{st}|$, and then associated with the area of a landslide by means of a circle with variable diameter. Landslides induced by the Haiyuan Earthquake (Figure 8) were clustered near ridge crests, with 65.7% of the landslides originating in the upper quadrant of slopes (normalized distance to ridge <0.4). This suggests that the upper parts of slopes are more sensitive to earthquakes in loess areas. Further, 9.32% of these landslides with the $|d_{top}|$ and $|d_{st}|$ are 0, with the area of 0.22 km^2 , this indicates that in some cases, entire slopes failed during the earthquake, and large landslides moved from ridges to stream channels with long travel distances.

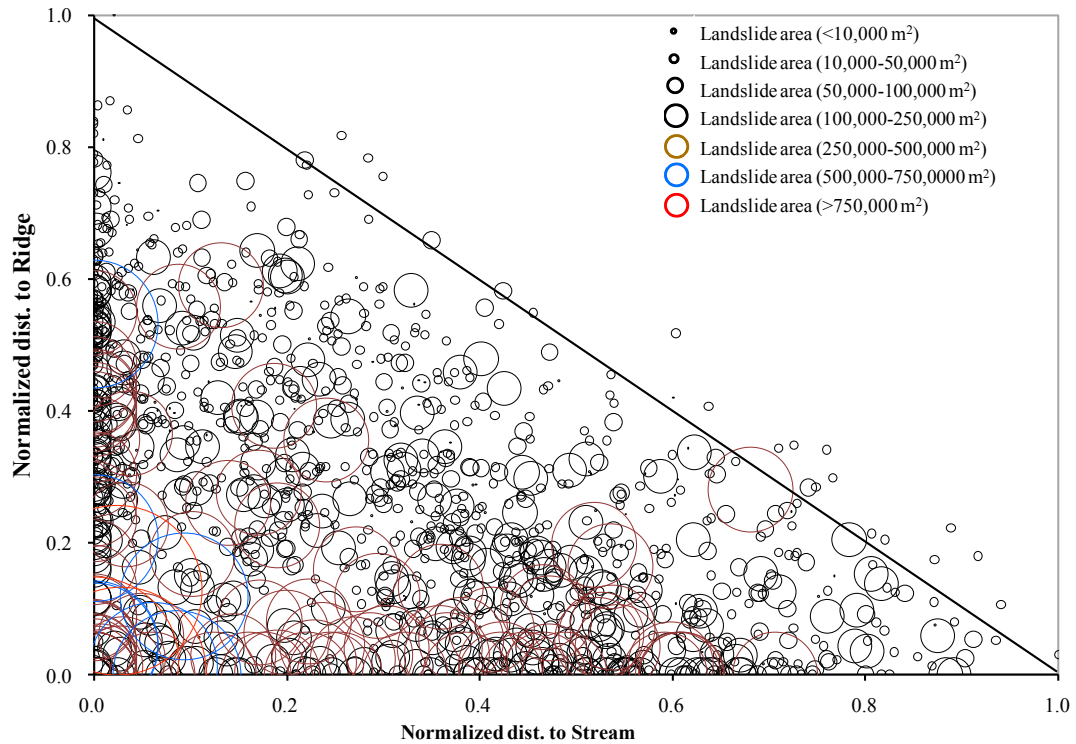


Figure 7 Location of landslides with respect to ridge crest and stream.

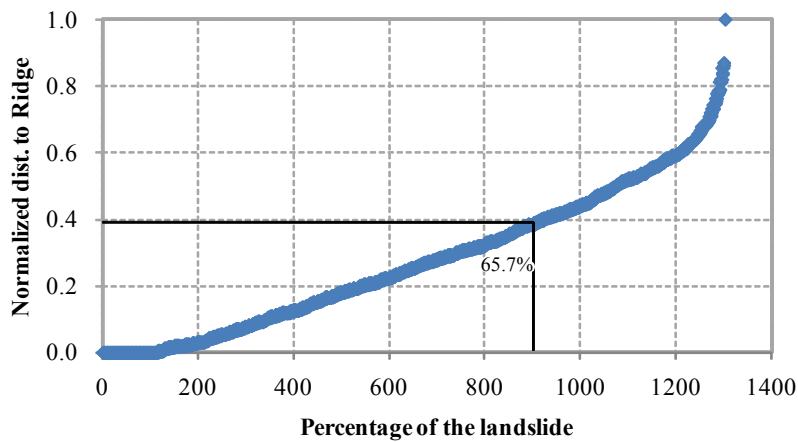


Figure 8 Percentage of the landslide with respect to ridge crest.

4.3. Landslide distribution by aspect

Aspect can affect landslide occurrence during earthquakes due to the travel direction of earthquake waves (Huang and Li, 2008; Sato and Harp, 2009; Xu et al., 2011). The distribution of coseismic landslides follows the rules of the so-called "back slope effect" (Huang and Li, 2008;

Sato and Harp, 2009; Xu et al., 2011), as evidenced by the Chi-Chi Earthquake in Taiwan (M_w 7.6, 1999) and the Kashmir Earthquake in Pakistan (M_w 7.6, 2005). According to the previous study, slopes facing the seismic source are less susceptible to landslides than the slopes parallel to the direction of travel as the earthquake waves (Huang and Li, 2008; Sato and Harp, 2009; Xu et al., 2011). The epicenter of the Haiyuan Earthquake was initially located in the western section of the fault and the rupture propagated southeast (Seismological Institute of Lanzhou, SSB. and Seismological Team of Ningxia Hui Autonomous Region, 1980; Burchfiel et al., 1991; Zhang and Wang, 1995). Figure 9 indicates that the landslide density on the northwest facing slopes (44.5%) was five times as that on the southeast slope (8.9%), while the area of the aspect of the slope distribution averaged in every facing. These observations differ from observations from other earthquakes (Huang and Li, 2008; Sato and Harp, 2009; Xu et al., 2011). The Haiyuan fault is a strike-slip fault with left-lateral motion. The Chi-Chi, Kashmir, and Wenchuan Earthquakes were all thrust-fault earthquakes (Burchfiel et al., 1991; Zhang and Wang, 1995). The direction of movement of the main block is the primary determinant of landslide occurrence in a strike-slip fault (Huang and Li, 2008; Sato and Harp, 2009; Xu et al., 2011). Furthermore, slopes with aspects opposite to the direction of movement were more susceptible to landslides than other slope aspects in the Haiyuan Earthquake (Figure 10). Superposition of displacement to the doubling of the outward acceleration at the free boundary. The acceleration direction of the slope caused by the block move is different in the different aspect of the slope. The acceleration direction is according with the slope aspect which is the opposite to the block move direction and generate tensile stress in the slope. And the compressive stress generated in the slope along the block move direction. So, the slope which is the opposite to the block move direction is trend to

failure due to tensile stress and the slope which is the opposite to the block move direction is not trend to failure due to compressive stress (Tang, 2008; Xu et al., 2011).

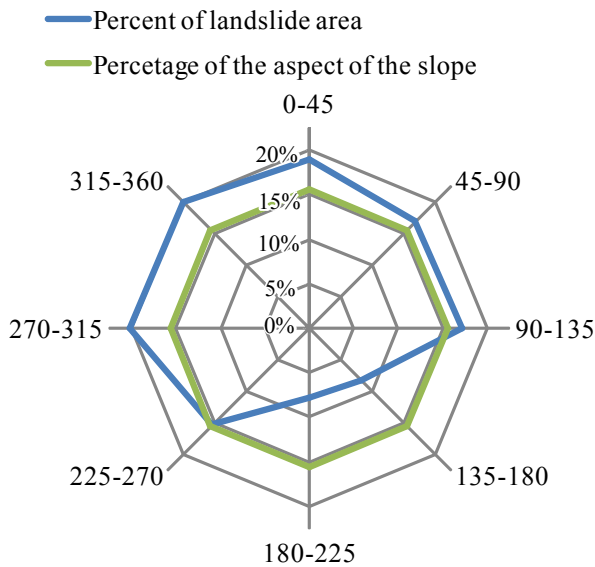


Figure 9 Location of landslides with respect to aspect.

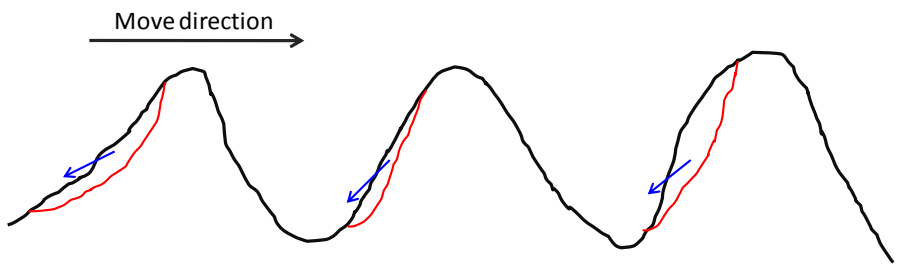


Figure 10 Landslides after the 1920 Haiyuan Earthquake were easily induced at slopes facing the opposite direction from that of the movement of the block

5.Characteristics of landslides triggered by the Haiyuan Earthquake

5.1. Landslide size

The 1920 Haiyuan Earthquake triggered 3,700 landslides within the range of the intensity of 9-12, with a total area of 177 km², over an area of about 21,000 km². The average landslide-point density and landslide-area density were 0.18 landslides/per km² and 0.85% respectively.

Proportionally, the greatest number of landslides occurred to the southwest of the eastern section of the Haiyuan fault. As compared to the Wenchuan Earthquake, the landslide number, area, and density were lower in the Haiyuan Earthquake event (Harp and Jibson, 1996; Lin and Tung, 2004; Owen et al., 2008; Dai et al., 2011).

The mean landslide area was 0.048 km^2 , which is greater than what is typical for landslides triggered by other earthquakes (Table 1). It is conceivable that some of the smaller landslides disappeared and were therefore not included in the analysis, thus raising the mean.

Table 1 The sizes and numbers of landslides triggered by earthquakes in recent years

Items	Study area (km^2)	Number of landslides	Landslide areas(km^2)	Average landslide area(km^2)
Northridge earthquake (Harp and Jibson, 1996)	10,000	11,111	23.8	0.00214
Haiyuan Earthquake	40,000	3,700	117.5	0.03162
Wenchuan Earthquake (Dai et al., 2011)	41,750	56,000	811.0	0.01448
Chi-Chi earthquake (Lin and Tung, 2004)	--	9,297	128.0	0.01374
Kashmir earthquake (Owen et al., 2008)	7,500	2,424	--	--

We examined the area-frequency distribution of the earthquake event by log-log coordinates (Figure 11). The largest landslide was 0.4 km^2 and the cumulative number-area relationship for landslides can be represented as the logarithm of the number N of landslides exceeding a given area A . Higher values of the gradient may reflect poor efficiency in identifying small landslides and this distribution may be attributed to the fact that some small landslides were never identified due to soil erosion and human activity.

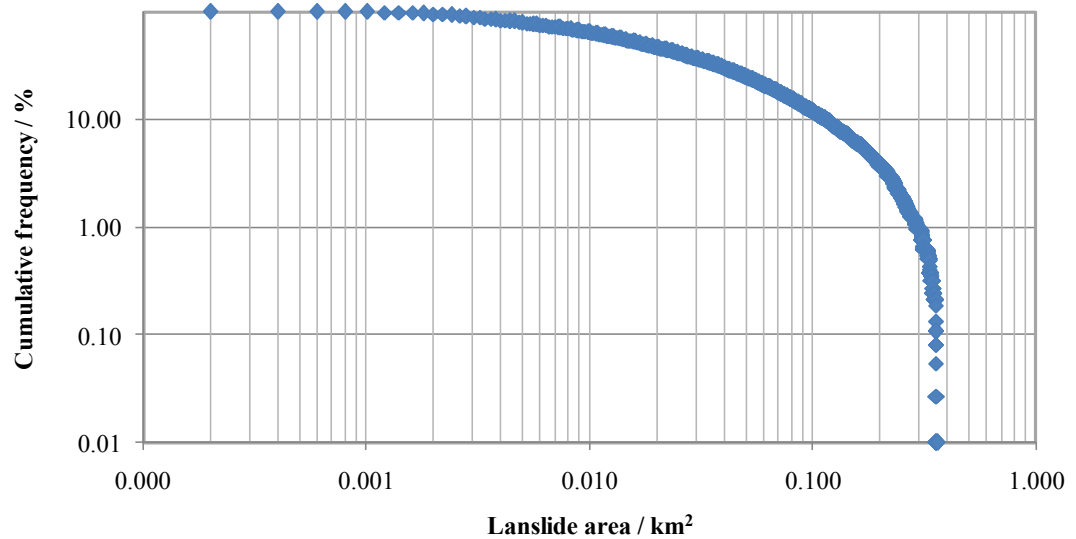


Figure 11 Landslide area cumulative frequency distribution

5.2. Travel distance

We examined the probability densities of equivalent coefficients of friction (landslide height (H) / landslide travel distance (L)) for 31 rock landslides and 57 loess landslides triggered by earthquakes (Figure 12). Thirty-one rock landslides with long travel distances triggered by the 2008 Wenchuan Earthquake, were studied, including eleven datasets from the literature and 20 datasets from field investigations immediately after the earthquake (Zhang and Yin, 2013). The datasets included information on landslide height, travel distance and volume. Fifty-seven loess landslides triggered by the 1920 Haiyuan earthquake and the corresponding landslides were predominantly concentrated in a small watershed.

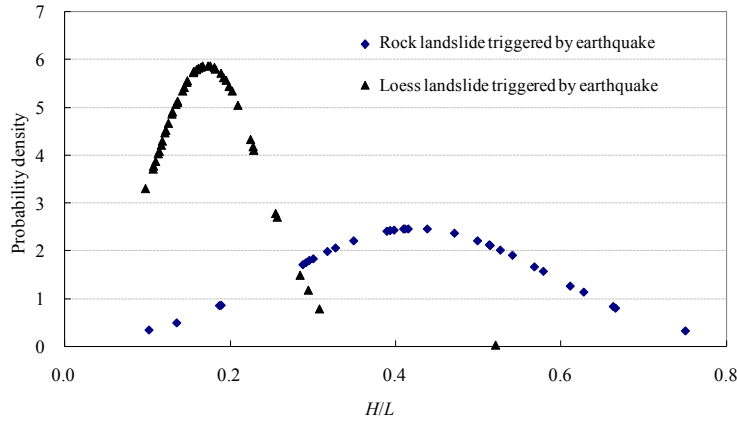


Figure 12 The probability densities of equivalent coefficients of friction

The H/L ratio of rock landslides triggered by earthquakes ranged from 0.1 to 0.75 with a mean of 0.42, while the loess landslides triggered by earthquakes ranged from 0.01 to 0.52 with a mean of 0.17.

The loess landslides induced by the earthquake were located in a different region of the graph from the rock landslides triggered by earthquake (Figure 13). The loess landslides move greater distances than rock landslides triggered by earthquakes, given an equivalent slope height. The relationship between the travel distance and equivalent slope height of the landslides induced by the Haiyuan Earthquake and Wenchuan Earthquake are $L = 8.308 * H^{0.935}$ and $L = 4.117 * H^{0.919}$. The best-fit curve for the former was much lower than the latter one. It indicates that the travel distance of loess landslides triggered by earthquake is much longer than rock landslides triggered by the Wenchuan earthquake at the same height.

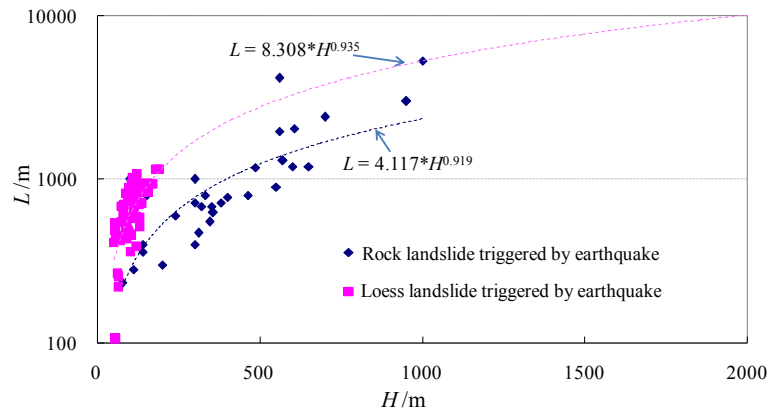


Figure 13 The empirical relationship between landslide height and travel length

5.3. Geohazard chain due to long run-out distance landslides

Due to the landslides long travel distances and the deposition of landslide materials in major stream channels, several quake lakes formed in the areas affected by the Haiyuan Earthquake. Currently, 51 lakes are still present, primarily in southwestern Xiji County (Figure 14).

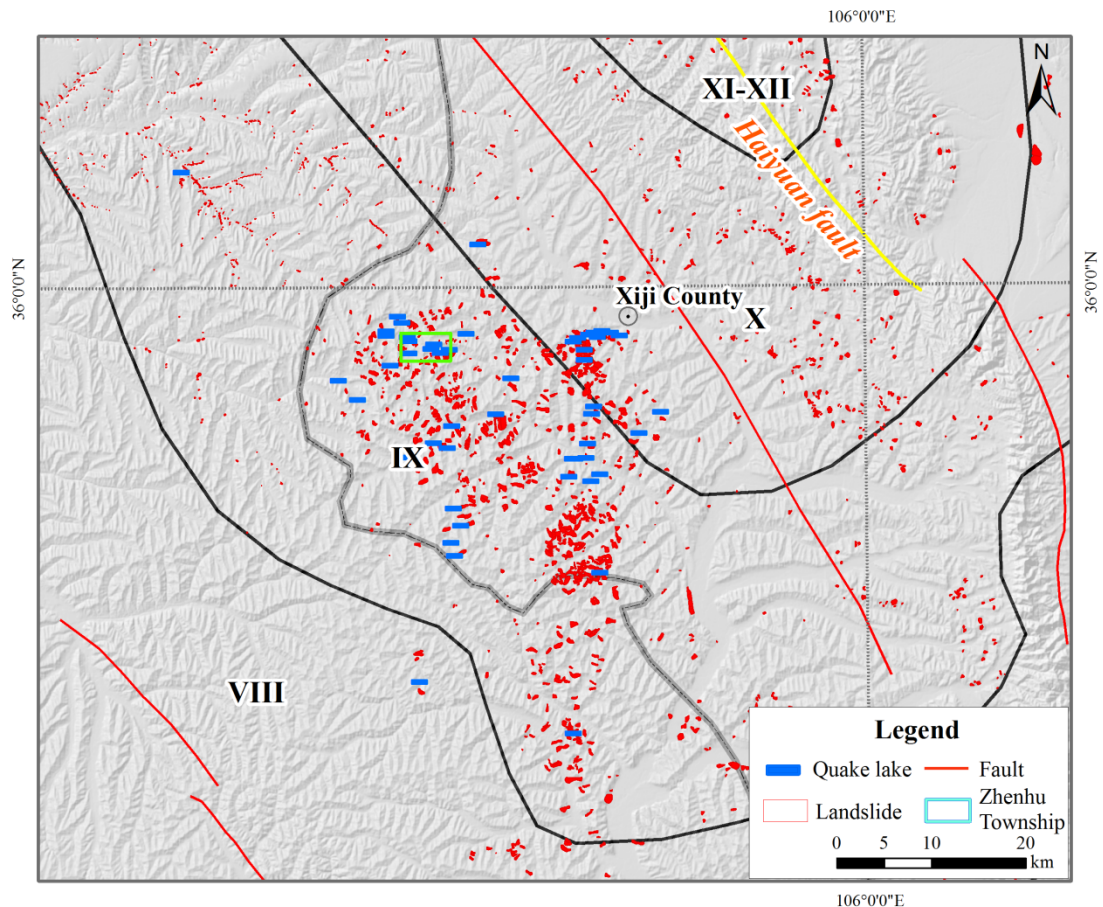


Figure 14 The quake lakes that formed after the Haiyuan Earthquake

Due to the human efforts for stabilization in the landslide-affected areas, the quake lakes became reservoirs for drinking water, agriculture, tourism and hydropower. Several urban settlements were constructed around the lakes, for example, Zhenhu (Quake lake) Township (Figure 15).

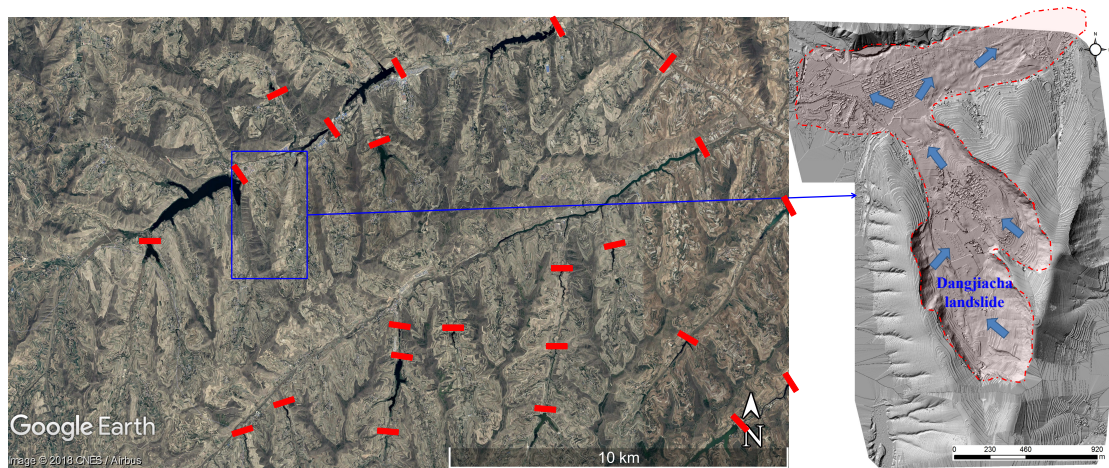


Figure 15 The group of quake lakes triggered by the Haiyuan Earthquake around Zhenhu (Quake lake) Township (Green box in Figure 14, the red rectangles are landslide dams)

6. Discussion

6.1. Area and number of landslides triggered by the Haiyuan Earthquake

We estimated total landslide volume (V) using a power-law landslide area-volume scaling relationship: $V = \alpha \times A^\gamma$, where α and γ are empirically-calibrated scaling parameters and A is the total landslide area. This is a widely used method to estimate landslide volume (Larsen et al. 2010). The area-volume relationship for landslides triggered by the Haiyuan Earthquake was obtained from field survey data. We investigated 89 well-preserved landslides to obtain and estimate their areas and mean depths, based on which the volume was calculated. Figure 16 depicts the relationship between the area and volume of the landslides induced by the Haiyuan Earthquake:

$V=4.170 \times A^{1.086}$. In general, the number of landslides triggered and landslides area is mainly affected by the magnitude of an earthquake (Xu et al., 2016; Havenith et al., 2016). However, the corresponding point for the Haiyuan Earthquake were located well below the regression line (Figure 17). The estimates of total volume of landslides which with the total area 177 km² associated with Haiyuan Earthquake was nearly 0.4×10^{10} m³. This suggests that many landslides were not identified due to the long time lag and as a result, the actual number of landslides were probably underestimated. Based on historical data and analysis of the relationship between landslides and earthquake magnitude, we estimated that more than 100000 landslides with a total area of 0.5×10^{10} m² were triggered by the Haiyuan Earthquake (Figure 17). There are more than 0.1×10^{10} m³ smaller landslide which were not identified due to loess rapid erosion and human activity.

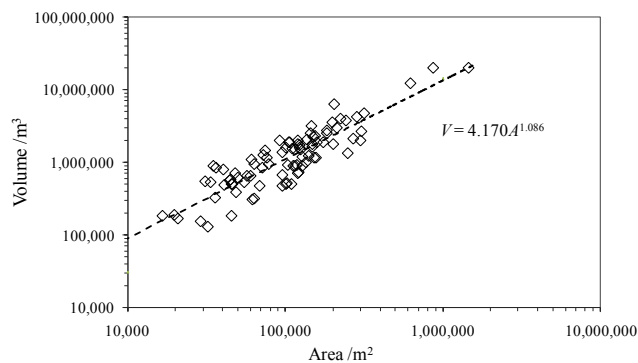


Figure 16 Landslide number and area, and their correlations with earthquake magnitude (revised from Keefer, 2002)

6.2. Causes of the uneven landslide spatial distribution

The spatial landslide distribution of the Haiyuan Earthquake was atypical case as compared to other comparable earthquakes. Several hypotheses have since been proposed to improve understanding of landslide distribution (Zhang and Wang, 1995; Zhang and Wang, 2007; 2014; Li

et al., 2015; Havenith et al., 2015). It is widely accepted that the larger landslides triggered by the Haiyuan Earthquake were primarily in loess (Lin and Wang, 2006; Zhang and Wang, 2007; Wang et al., 2014; Li et al., 2015). Figure 18 shows the loess depth distribution in this area, indicating that it was deepest in west of the study area. Considering this fact, it is a question mark that the landslides were focused in only the southwest. This may be because the northwest landform is a gently sloping loess dome. In addition to this, the mountain ranges separate northwestern Xiji County from the Haiyuan fault. Therefore, the Haiyuan fault's strike follows the northeastern foot of the range, and the displacement triggered by the Haiyuan Earthquake was sharply attenuated by the mountain range. However, the absence of mountains between the Haiyuan fault and the loess areas to its southeast, paved the way for a greater number of landslides to occur in this area. Finally, the left block of the Haiyuan fault moved from northwest to southeast, indicating that stress was concentrated towards the southeastern section of the fault and paving way for a larger number of slope failures.

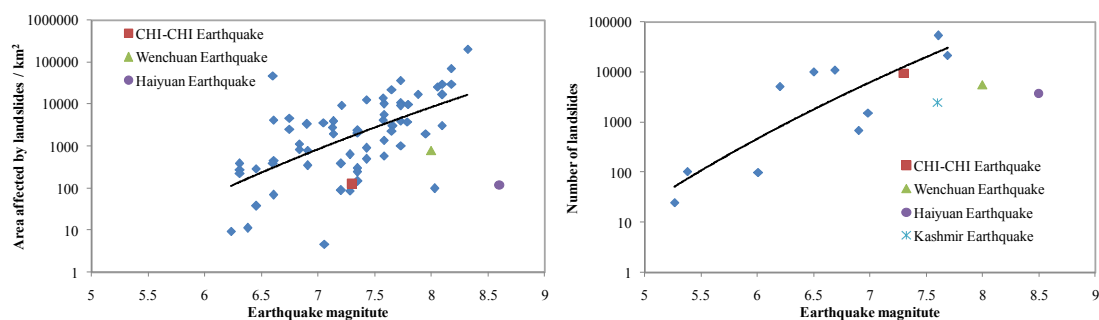


Figure 17 Loess depth distribution in the area affected by the 1920 Haiyuan Earthquake

6.3. Number of loess landslides with long travel distances

Loess is characterized by macro-pores, vertical joints, loose texture and quake sensitivity, which makes it prone to landslides (Derbyshire, 2000; Dijkstra, 1995; Xu et al., 2007; Zhang et al., 2009; Zhang and Liu, 2010). Loose loess soil can be easily liquefied during an earthquake, and

this process is known as dynamic liquefaction. Ter-Stepanian (1998) suggested that flow-type loess landslides were triggered by high pore air pressure during a quake. Loess landslides were classified as a type of rapid soil flow by Keefer (1984). The widely used criteria for the liquefaction potential of fine particles were originally proposed by Wang(1979). Soil can undergo liquefaction if it meets two conditions: 1) particles finer than 0.005 mm comprise less than 20% of the total; and2) that the saturation water content (W_s) to liquid limit (W_L) ratio is greater than 0.9. We conducted soil tests on three loess soil samples from Xiji County (Table 2), the particles less than 0.005 mm in diameter comprised 13%-14% of all particles, the liquid limit was between 28% and 29%, and the calculated water content of fully saturated samples was between 36% and 39%. Hence the W_s/W_L ratio was above 0.9 (values of 1.25, 1.37 and 1.27). This confirms that the loess in Xiji County is sensitive to liquefaction during earthquakes and is likely to produce landslides with long travel distances.

Table 2 Physical parameters of the loess in Xiji County

Items	Particle size/ % <0.005 mm	Particle size/ %0.005-0.0 75 mm	W_P /%	W_L / %	W_C /%	W_s /%	W_s/W_L
Sample 1	13.90	80.99	20.00	28.70	11.60	36.00	1.25
Sample 2	13.02	81.30	20.20	28.50	14.30	39.00	1.37
Sample 3	14.67	83.30	21.80	28.20	14.20	36.00	1.27

7. Conclusions

The 1920 M_w 8.5 Haiyuan Earthquake triggered 3,700 landslides in areas with shaking intensities of up to 9, with a cumulative area of 177 km², over an area of about 21,000 km². The average landslide size was 0.048 km². The landslides were concentrated in a zone 40-55 km from the Haiyuan fault. The distribution characteristics were not symmetrical around the fault, with the

greatest landslide concentration occurring at a distance of 40-55 km from the fault on the western side, and on the eastern side the landslide concentration decreased with distance from the fault which is not similar with that triggered by other earthquakes.

Landslides induced by the Haiyuan Earthquake were clustered near ridge crests, with 65.7% originating in the upper 40% of slopes. Slopes oriented away from the direction of movement of the block were more susceptible to landslides than those oriented towards or perpendicular to the direction of movement and there is no back-direction effect in landslides triggered by Haiyuan earthquake. Co-seismic loess landslides run out distance is longer than rock landslides which gives an equivalent landslide crest height. Liquefaction is a possible explanation for long run-out and our results are consistent with this explanation, suggesting that the loess in the study area is sensitive to liquefaction during an earthquake. The deposition of landslide materials into main river channels had resulted in the formation of 51 quake lakes in this region. According to historical records and analysis of the relationship between landslides and earthquake magnitude, we estimated that over 5,000 km² area in the study area has exposed to landslides, and 100,000 landslides have been directly or indirectly triggered by the earthquake.

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